TITLE: ESM-Sensors for Tactical Information in Air Defence Systems

# ESM-Sensors for Tactical Information in Air Defence Systems

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**Abstract**

The main purpose of this paper is to inspire investigation efforts in clarifying whether ESM-sensors can become components of a cost-effective Integrated Air Defence System for an International Reaction Force, as we think that the potential of ESM-sensors in air defence is not yet fully recognized and analysed. The planning and conducting of air attacks with today's and tomorrow's technology seem to increasingly make use of electromagnetic emissions from airborne platforms. ESM-sensors can pick up these emissions; such sensors are likely to become more available due to the current technical development. The paper tries to enlighten the applicability of ESM-sensors in Air Defence Systems by presenting and discussing the different types of information they supply. An analysis of position accuracy is presented. Some principles for integrating ESM-sensors in a radar-based Air Defence System are suggested.

## 1. Introduction

ESM-sensors (Electronic Support Measures) may be seen as tactical versions of ELINT-sensors (Electronic Intelligence) (1) being one part of modern electronic warfare (2). ESM-sensors are currently not regarded as significant and cost-effective suppliers of tactical information in air defence, possibly caused by their type of information, their relative high price, and the fact that they depend on signal-emissions from an unpredictable adversary. This rationale is challenged by the ongoing technical development, likely relevant for an International Reaction Force.

True enough, ESM-sensors depend on emitted electromagnetic signals from the adversary. However, an increasing number of possible threats to an International Reaction Force normally emit signals, as indicated in section 2. Most of the platforms and emitters could be in the inventory of a potential future adversary. Proper ESM-sensors may supply valuable tactical information from these emitters. Also, if knowing the presence of the ESM-sensors, the adversary may restrict himself beneficially for the Reaction Force.

The current technical development of small and relatively cheap microwave components, signal processing devices and computers are likely to make ESM-sensors more available and their information more easily transformed to useful tactical information. ESM-sensors exhibit a quite wide spectrum of capabilities, as indicated in section 3, and improvements are likely. Their more salient features in this context are to detect objects in a complementary way and to characterize the detected signals enabling an identification of the emitters and platforms. By combining bearings, elevations, and time arrivals from different ESM-sensors, the position can be obtained.

Tactical useful information from the ESM-sensors include detection and verification for alerting, identification of the threat, possibly with a coarse position, or ultimately positioning and tracking of the emitter, as described in section 4. The position information from the ESM-sensors is important for associating the ESM-information with tracks from radars, which still are the basic information source in air defence in the foreseeable future. The position accuracy of ESM-sensors highly depends on the characteristics of the emissions, the measurements, the number of sensors and their geometry, as shown in the analysis of section 5. ESM-sensors use only the direct signals from the emitter to the sensor, but other passive sensor concepts are demonstrated, see section 5.

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The data from ESM-sensors have to be integrated into the radar-based Air Defence System to fully utilize their tactical information. This may involve a central Multi Sensor Tracker (MST) integrating different types of sensors. However, we suggest that this is done by "graphical integration" after a first "preprocessing" in an ESM-system. These and some other aspects of Data Fusion are discussed in section 6.

Section 7 makes a summary of important pros et cons of ESM-sensors and discusses critical issues of their applicability for the air defence of an International Reaction Force. ESM-sensors may be worthwhile to integrate in such a system, but a conclusion requires a lot more investigations.

## 2. Unclear and Diverse Air Defence Threats to a Reaction Force - Many Emitters Involved?

An International Reaction Force may be employed in a wide range of situations where the threats are quite unclear and diverse. Specifying relevant scenarios is therefore almost impossible. This section rather gives a brief outline of various general air defence threats and the use of emitters in association with such attacks. The purpose is not to predict the likely nature of an attack and participating platforms, but to point out that a large spectrum of conceivable threats emit electromagnetic signals. Figure 1 shows a number of platforms that may be present in a scenario and a number of different classes of emitters.

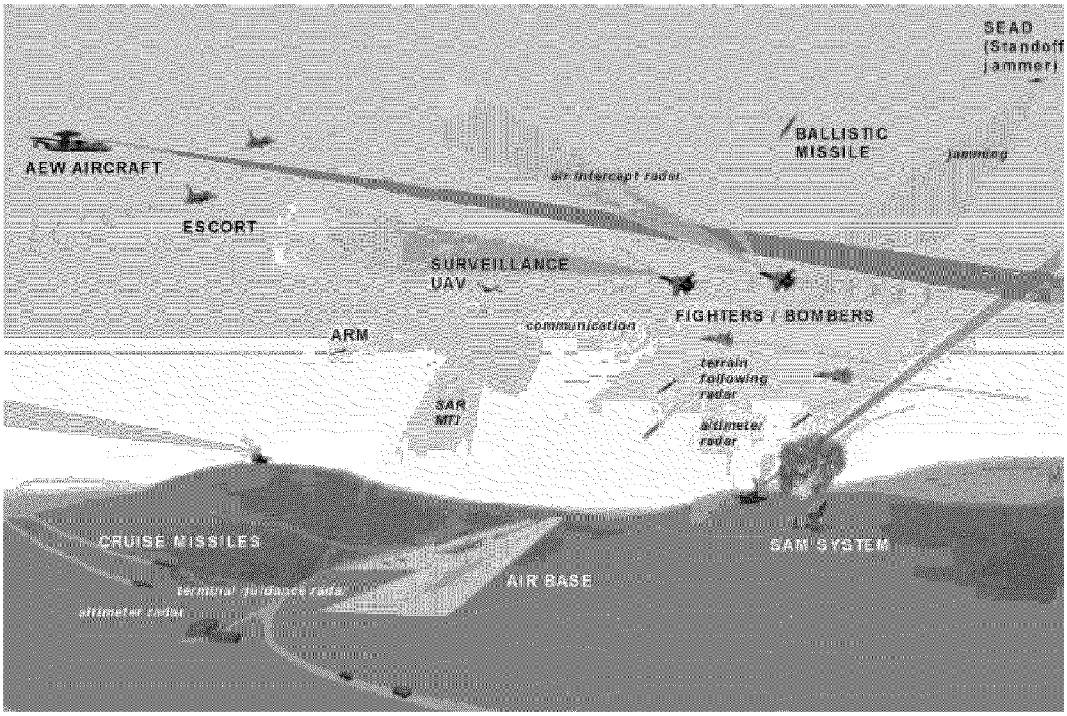


**Figure 1 Examples of threats with emitted signals (red) and some threats that do not emit**

Today the threats facing an International Reaction Force are unlikely to include the more sophisticated weapon systems. However, one can not rule out the possibility of a technically advanced adversary in a future conflict, at least possession of some new technology. As referenced in the US Space Command's Long Range Plan of 1999: "Advanced technology can make third-class powers into first-class threats." (Dick Cheney, former Secretary of Defence). The aerospace is an increasingly important part of the battlefield. The following observations regarding the development and proliferation of the different weapon categories can be pointed out:

- Fighters and attack aircraft are used by an increasing number of countries. In the near future conceivable adversaries would presumably use fighter-bombers carrying unguided bombs. Among the major military powers there is a trend towards the use of precision-guided munitions (PGMs) delivered from longer ranges.
- Up to now sophisticated land attack cruise missiles have not been widely proliferated, but the technology needed to produce UAVs is readily available. Armed UAVs and technically simple cruise missiles constitute a future threat.
- Tactical ballistic missiles (TBMs) is an increasing threat.
- UAVs for ground surveillance and targeting are likely to be available for potential adversaries in the future.

Many of these threats emit signals. The effectiveness of aircraft and weapon systems seems more and more to rely on advanced electronic equipment, including a variety of electromagnetic emitters. The following emitters might be important:

- Air intercept (AI) radars (powerful emitters used by fighter aircraft)
- Navigation- and terrain-following radars (might be incorporated as modes in AI-radars)
- Altimeters (relatively low-powered emitters used by aircraft and cruise missiles)
- Radars for ground surveillance, i.e. SAR and Ground MTI (carried by UAVs or special aircraft or incorporated as modes in AI-radars)
- Communication links
- Jammers

An International Reaction Force has to pursuit information superiority. This might be particularly important in scenarios with a heterogeneous Reaction Force and diverse and unclear threats. Emitted signals from airborne platforms can tell a lot about the tactical situations and ESM-sensors may therefore constitute a valuable information source for the Reaction Force.

## 3. A Sketch of Current and Future ESM-sensor Capabilities

ESM-sensors have been around since Word War II to detect and characterize electromagnetic emissions (radar, link, voice etc.). They are used on land, at sea, in the air and in space, and therefore come in a lot of different configurations (technology, quality, size and price).

ESM-sensors have to cover a very wide frequency range, traditionally 1/2 to 18 GHz, and in the future even higher. To achieve a high probability of intercept (POI) for these emissions, each frequency within the range should ultimately be continuously covered. However, covering a wide frequency range is often contradictory to other ESM requirements like the ability to detect, sort, and measure parameters of the radar signals (2).

ESM-receivers based on a number of different principles and technologies have been developed. The most popular receiver type has been the so-called Instantaneous Frequency Measurement (IFM) which coarsely measures parameters of the radar pulses over a wide frequency range. The main drawbacks of this receiver are its relative low sensitivity and instantaneous handling of only one signal. Some ESM systems use an additional high sensitive narrowband (superhetrodyne) receiver for precision measurement of signals of special interest.

It has long been acknowledged that having a number of narrowband receivers in parallel, a channelized receiver, would be the best solution since it combines high POI with high sensitivity and multiple emission capability. The disadvantages of the channelized receiver have been its complexity, resulting in high cost, power consumption and large size. The last five years developments in microwave components and packaging technologies have made the channelized receiver a more attractive solution and development of such receiver are going on.

Another important and fast evolving technology that will improve future ESM-sensors is the increased speed in sampling and digital processing of signals (3). Signal bandwidths of a few hundred megahertz can be sampled and digitally processed. Today the major limitations are dynamic range of the analogue-to-digital converters and the speed of the signal processors. There are a number of advantages by using digital signal processing: More accurate information can be extracted from both single pulses and from pulse trains. The same hardware can perform different signal processing by use of specialized software, which will be important for detection of Low Probability of Intercept (LPI) radars.

The antennas determine the spatial coverage of the ESM-sensor, which is normally 360° in azimuth and typically 20° in elevation (but depends on the application). The antenna configuration also contributes to the direction finding capability, i.e. the angle-of-arrival (AOA) measurements. Omni-directional antennas give 360° coverage and therefore 100% POI with respect to direction, but they have low gain, which gives low system sensitivity, and no AOA. A 100% POI can also be obtained with a number of directional antennas arranged in a circle (often 6 to 8). This leads to higher antenna gain, and AOA can be calculated from the signal differences between two adjacent antennas. A third principle is to use a highly directive spinning antenna with high gain, but with a lower POI. One ESM-sensor may use several antennas to improve its performance.

As a general summary one may state that the parameters characterising ESM-sensors generally span a wide range (2) (3) (4); POI (<1% to 100%), sensitivity (-40 to -110dBmi), antenna gain (-5 to +25dBi), accuracy of frequency-of-arrival (FOA) (50Hz to 10MHz), time-of-arrival (TOA) (1ns to 1ms), AOA (0,1° to 10°), pulse density (100k to 10Mpulses/s). Other signal characteristics may be measured for pulse sorting and emitter identification, the latter requires an emitter library. In addition to the techniques used in the ESM-sensor, the performance also depends on the actual emissions. An ESM-sensor instantly (100% POI) measuring the parameters with the best performance available would be very costly and therefore tradeoffs have to be accepted. One solution is to use a high POI solution for signal detection, and additional specialized hardware for precision measurements. Since the actual solution highly depends on the operational requirements, a further discussion is outside the scope of this paper.

Selecting appropriate sensor capabilities for use in Air Defence of an International Reaction Force is not an easy task. The blend of emitters likely to observe, their tactical use, and the resulting price of the ESM-system have to be taken into account. As a starting point for an accuracy analysis we choose the following nominal values for the measurement uncertainty ($1\sigma$):

| | |
|---|---|
| Bearing: | 1.0° |
| Elevation: | 1.5° |
| Time arrival: | 70 ns |
| Frequency: | 100 Hz |

The values applies to a single sensor, and by assuming independent errors between pair of sensors a TDOA gets an accuracy of 100 ns, and FDOA an accuracy of 140 Hz (resulting from a square sum of the two components).

## 4. Tactical Contributions from ESM-Sensors in Air Defence

The ESM-sensors may produce different types of tactical information to an Air Defence System. This depends on the operational situation and the choice of ESM sensor capabilities - a choice within a quite wide spectrum, as indicated in the previous section.

An example of a valuable piece of information is a record of detected signals as evidence of what happened in a specific situation. However, this is not "tactical information" if it can not be used in the situation itself. A piece of tactical information is the very first detection of a hostile platform by an ESM-sensor. Since the ESM-sensors constitutes a complementary "sense" of the Air Defence System, it might well supply the very first warning. The value of such a contribution highly depends on the gained alerting time and on the gained understanding of the tactical situation by the supplied information. Even if the ESM-detection did not happen to be the first, it may confirm a detected threat and supply complementary information for a better understanding of the situation.

The ability to deduce identification information from the signals detected, is the more valuable benefit of ESM-sensors. Different levels of identification might be obtained according to the accuracy of the parameters measured, the prior data gathered in an emitter library, and the applied methods and interpretation-software. One level is to determine the class of emitter (AI-radar, altimeter etc.); another is to identify the type (product name) of the emitter. In some cases individual emitters might be distinguished and recognized by specific signatures of their signals ("fingerprints"). The number of emitters might be deduced fairly independent of the identification level. The type of hostile platform may be deduced when the library contains emitter-platform associations.

Radars are unquestionably the core sensors in air defence. Identifying the tracked objects by radars may be possible, but it is difficult. The association of ESM-identifications to radar-tracks would be of great importance. This would reduce the weapon engagement time and avoid engagements of friendly platforms ("blue on blue"). Such track-identification might be possible without positional information from the ESM-detections due to the situation and prior tactical knowledge. However, the association normally requires positional information to decide which among several tracks the identified signals come from. In dense situations this might mean independent ESM-system tracking. In other situations a medium accurate bearing of the identified signal might be sufficient.

As indicated in the next section, ESM-tracks may be quite accurate, even compared to radar tracks. This might be used to improve the radar track accuracy, either by track-track correlation or by using a Multi Sensor Tracker. This is especially useful in situations where the radars do not function at their best like in heavy clutter or jamming. Theoretically, the ESM-tracks can be based on the jamming signals degrading the radars. In such a situation the ESM-system will truly be a complementary element to the radars.

In cases where the airborne platforms constantly use detectable emitters, a fairly complete air picture can be generated from the ESM-sensor data. ESM-system tracking opens for weapon firing and guidance. The next section makes a position accuracy analysis of ESM-sensors that is relevant for the question of tracking.

## 5. Position Information in Combined ESM-Sensor Measurements

As indicated in the previous section, the position-information is tactically important for several reasons. The geometry-related position accuracy of ESM-sensors seems not to be well known, and is therefore treated in some detail here. Interested readers can hopefully expand the results to other parameter-settings and geometries.

Here we only treat position estimation by the direct signals from the emitter to the sensors when bearing, elevation, and TDOA (Time Difference Of Arrival) can be measured. The reader should be aware of other methods of passive sensor positioning. One is a bistatic radar "hitchhiking" on a rotating search radar (5).

Other may use the bistatic principle with additional Doppler-measurements using commercial FM-radio and TV-stations as the emitters (6) (7). A third is to use terrain-reflections from a wide-band jammer (8).

As stated, measurements from two or more ESM-sensors have to be combined in order to estimate the position of the emitter. The regarded ideal measurements expressed in a Cartesian coordinate system are:

$$\varphi_{i,j} = \arctan\ [(x_j - x_i) / (y_j - y_i)]\theta_{i,j} = \arctan\ [(z_j - z_i) / \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}\,]$$

$$\Delta\tau_{i1,i2,j} = (1/c)\ (r_{i1,j} - r_{i2,j})\ ,$$

$$r_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}$$

where

| | |
|---|---|
| $\varphi_{i,j}$ | bearing of emitter $j$ from sensor $i$ |
| $\theta_{i,j}$ | elevation of emitter $j$ from sensor $i$ |
| $\Delta\tau_{i1,i2,j}$ | time difference of a signal from emitter $j$ to the sensors $i1$ and $i2$ |
| $(x_j, y_j, z_j)$ | position of emitter $j$ |
| $(x_i, y_i, z_i)$ | position of sensor $i$ |
| $r_{i,j}$ | length of $[(x_i, y_i, z_i) - (x_j, y_j, z_j)]$ |
| $c$ | the speed of light |

A bearing measurement theoretically restricts the position of the emitter to a vertical plane through the sensor and emitter. An elevation restricts the position to the surface of a cone. A TDOA restricts the position to a hyperboloid through the emitter having the two sensor- positions in the focal points. Combining several measurements may theoretically restrict the position to a point. Each type of measurement has an accuracy depending on the measurement principle, the technical solution and the signal to noise ratio. Geometrically, the measurement uncertainty adds a "thickness" to each of the three types of surfaces. Figure 2 illustrates the three types of measurements with their uncertainty from two out of a four sensor-configuration used throughout this paper: three sensors in a regular triangle 20 km from a central forth sensor.

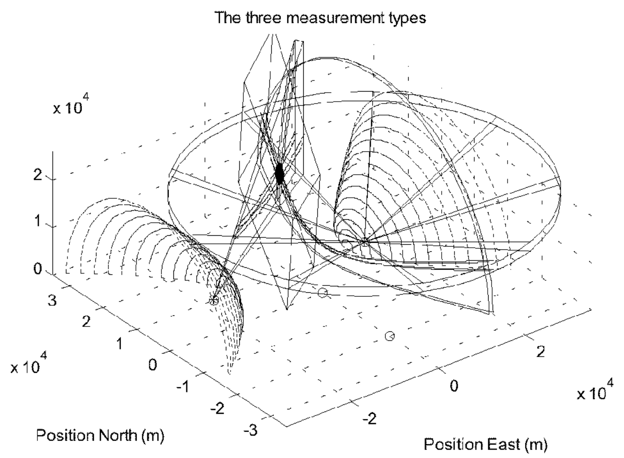


**Figure 2 Three types of "measurement volumes" (blue) and their intersections (red)**

*The "volumes" are from a bearing, an elevation, and a TDOA with measurement uncertainty of 1.0°, 1.5°, and 10x100ns respectively. The three "pair intersections" (red curves) make a "box" around the object which is enlarged 15 times. The box corresponds to the position uncertainty; it increases with distance and poor intersection geometry. (The two other sensors in the four- sensor example of the paper are indicated.)*

The accuracy of the calculated position depends on the local "surface thickness" and the intersection geometry of the surfaces defined by the measurements; the more orthogonal, the better. The following formulas can be used for calculating the "surface thickness" for a coarse analysis of a specific geometry:

$$ds_\varphi = 2r_{i,j} \sin \sigma_\varphi$$
$$ds_\theta = 2r_{i,j} \sin \sigma_\theta$$
$$ds_{\Delta\tau} = \frac{\sqrt{2}\, c}{\sin \frac{\alpha_{i_1,i_2,j}}{2}} \sigma_{\Delta\tau}$$

where

| | |
|---|---|
| $ds_m$ | $m = \varphi, \theta, \Delta\tau$, the local "measurement surface thickness" |
| $r_{i,j}$ | length of $[(x_i, y_i, z_i) - (x_j, y_j, z_j)]$ |
| $\sigma_m$ | $m = \varphi, \theta, \Delta\tau$, the measurement uncertainty |
| $\alpha_{i1,i2,j}$ | the angle between the lines from the emitter $j$ to each of the sensors $i1$ and $i2$ |

The uncertainties used in Figure 2 are 1°, 1.5°, and 1μs, the latter 10 times the nominal value for illustration purpose. The ranges to the emitter (x=14 km, y=31 km, h=6 km) are 38 km and 22 km, the angle between the lines-of-sight to the sensors are 64°, giving the approx. "surface thickness" of 1.3 km (bearing), 1.1 km (elevation), and 0.6 km (TDOA). Figure 2 also shows the intersection between all three "thick surfaces" making up a "box" corresponding to the position uncertainty of the three measurements. The shape and size of the "box" change according to the 3-D position of the emitter even if the measurement uncertainties do not change. Here the intersection geometry is fairly favourable, but other positions may skew and stretch the remaining "box" to a considerable size. The reader hopefully gets a "feeling" of the mechanism of position uncertainty shaping by the measurement uncertainties and the geometry.

Figure 3 is included to give a better understanding for the use of TDOA for position estimation. The topic here is the geometry of the intersections of hyperboloids (the measurement uncertainty now disregarded). The sensors in Figure 3 are three out of the four regularly positioned sensors. Two families of hyperboloids are indicated; each hyperboloid is made up of points having the same TDOA with respect to the sensors in the hyperboloid focal points. The red curves are the intersection of two hyperboloids, one from each of the families. All the points on a single red curve have the same TDOA with respect to both pair of sensors. (Using the hyperboloids from the third pair of the three sensors, results in the same intersection curves.) Notice that all curves intersect the horizontal plane perpendicularly, and that the curves are close to horizontal near the extensions of the lines connecting any two sensors (the base-lines).

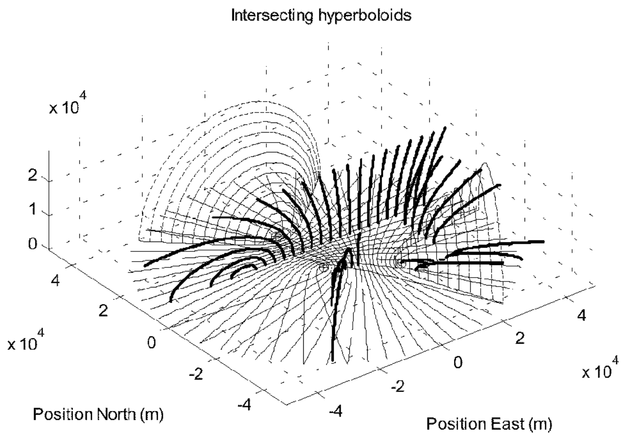


**Figure 3 Hyperboloid families (black/blue) from three sensors with intersections (red)**

*One hyperboloid of each family is shown (black) with intersections of the horizontal plane (blue). Hyperboloid intersections (red) start on four different lines parallell to the axes. Starting points near the extension of any base-line make curves turning down again; horizontal parts of the curves are quite close to these extension lines. One region makes intersection curves almost vertical.*

Figure 3 shows that TDOA from three sensors are insufficient for calculating the position of the emitter in 3-D. However, with a correct assumption of low altitude compared to the sensor-distances, TDOA is sufficient. An additional elevation measurement from one of the three sensors is sufficient to decide the emitter position in 3-D provided that it is not located on a near horizontal section of the associated intersection curve. Also, a single bearing can do this job provided the emitter is not located near a vertical part of the associated intersection curve. As seen, together with TDOA, an elevation may give position information (North/East) and a bearing may give altitude information. Reference (9) describes a TDOA-system with a geometry similar to that in Figure 3 using altitude readings from the aircraft itself to obtain the position.

A statistical approach for analyzing the position accuracy mechanism indicated in Figure 2 is to calculate the so-called Cramer Rao Lower Bound (CRLB). This is a covariance matrix defining a near achievable, lower bound of a zero mean state estimator. This matrix is the inverse of the so-called Fisher information matrix, and is defined by a simple matrix expression based on some general assumptions. The covariance expression is listed below; interested readers are referred to standard estimation theory for more details, one example is (10).

$$P_{CRLB} = \left[ D^T P_W^{-1} D \right]^{-1}$$

where

$P_{CRLB}$ The Cramer Rao Lower Bound (a covariance matrix)

$D$ The linearized measurement matrix, where the matrix elements are:

$$d_{ml} = \frac{\partial}{\partial x_l} h_m(x), \text{ where } h_m ,$$

$m = \varphi, \theta, \Delta\tau$, are the listed measurement expressions , and $l$ is the index of the state vector (generally positions)

$P_W$ The measurement error covariance matrix

When the covariance matrix is known, one can calculate ellipses of constant error probability density assuming a gaussian distribution of the measurement errors. Error ellipses illustrates nicely the uncertainty in a simple situation, but not here with geometries implying a large span of the accuracies. The CEP measure (Circular Error Probable) is therefore used instead. This is the radius of a circle around the true position that statistically contains 50% of the position estimates. The CEP is a function of the lengths of the half axes of the ellipse. In a circular ellipse ($\sigma$min/$\sigma$max=1), CEP/$\sigma$max= 1.18; in an extremely long ellipse ($\sigma$min/$\sigma$max=0), CEP/$\sigma$max=0.675. Figure 4 shows the position accuracy of bearing intersections of two sensors. Bearings to five emitters are shown together with samples of error ellipses and the resulting CEP. As seen, the position accuracy is here highly dependent on the geometry, which is the general rule for ESM-sensor positioning.

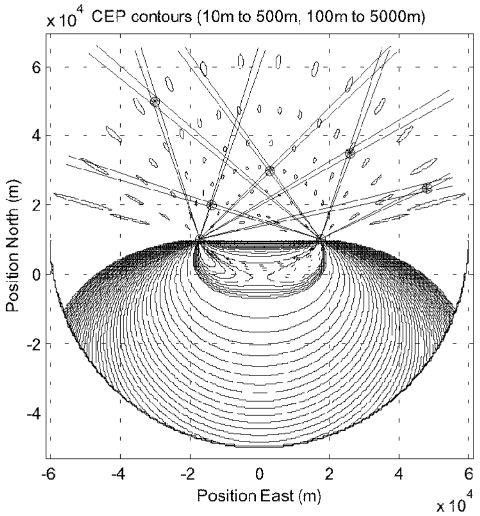


**Figure 4 Bearing intersection accuracy by two sensors (five targets present)**

*Only the bearing uncertainty limits (1.0°, 1$\sigma$) are drawn. Corresponding error ellipses (1$\sigma$) are shown in positions at fixed distances from the midpoint of the two sensors. The equivalent CEP-values are shown in the (symmetric) lower half plane.*

Figure 5 shows examples of the position accuracy obtained by bearings and TDOA from the ESM-sensors forming a regular triangle. The diagram is divided in three equal sectors to show the accuracy of bearings alone, of TDOA alone (assuming known low altitude), and the combination of the two. Each one of the three CEP contours covering 120° is symmetric and representative for the total 360°. As seen, TDOA gives poor position information near the extension of the lines connecting the two sensors (the base-line). The accuracy of combined bearings and TDOA is at least as good as the best accuracy of each of the two. In the central region bearings give approx. 400 m CEP, while TDOA gives approx. 30 m CEP.

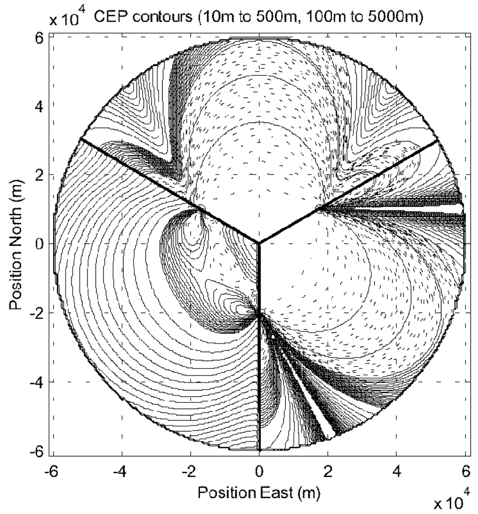


**Figure 5 CEP from bearings and TDOA of three sensors forming a regular triangle**

*Bearings are measured with uncertainty 1° (1σ), time arrivals with 70 ns (1σ). The left 120° sector shows CEP from bearings from the three sensors in a regular triangle. The right sector shows CEP when only TDOA are used, while the upper 120° sector uses both bearings and TDOA giving a CEP at least as good as the best of the two with a single type of measurements.*

Figure 6 shows the result when using TDOA only from all four sensors; four are needed to enable a 3-D positioning with TDOA only. This diagram is also divided into sectors that can be duplicated (flipped around the sector borders) to represent the total 360°. The position accuracy is shown in the lower third of the circle, while the rest is altitude accuracy (1σ). This sector of 240° is divided into four slices of 60°, each representing different altitudes. The altitude accuracy highly depends on the altitude of the emitter. It is quite poor at low altitudes, as can be realized from Figure 3 since the intersection curves of hyperboloid pairs intersect at a small angle here. Notice that the altitude uncertainty has local minima somewhat outside the three surrounding sensors, while the position uncertainty does not have such minima. Both the position- and altitude accuracy are best at the centre of the sensor-configuration.

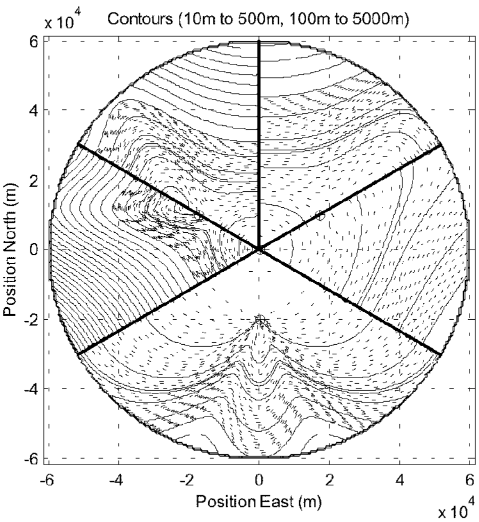


**Figure 6 CEP and four altitude RMS of TDOA from four sensors**

*Time arrivals are measured with uncertainty 70ns (1σ). The lower 120° sector shows CEP at zero altitude. Each of the 60° sectors show the altitude RMS from different altitude levels; from left to right: 2500m, 5000m, 10000m, and 20000m.*

Rules to extend the results of Figure 4, 5, and 6 to other parameter values should be mentioned. As seen from the expression of CRLB, the uncertainty is proportional to the measurement uncertainty. As for the linear scale of the geometry, different principles apply to angle measurements (bearing and elevation) and TDOA. When angle measurements are the dominating position source, the position uncertainty is proportional to the scale. This mean that the position uncertainty of a point referred relatively to the sensor configuration is doubled if the scale is doubled. When TDOA is the dominating position source, the uncertainty is independent of the scale. When other sensor configurations are used, the results will not be as easily modified. We then suggest to use the geometric approach mentioned in relation to Figure 2.

As seen from Figures 4, 5, and 6, CEP increases more than proportionally with the range from the centre of the sensor configuration. Figure 4 also indicates that the error ellipses get stretched at long distances, which also happens when TDOA is involved. This means the position information at long distances turns into a direction information governed by the "thickness" of the long ellipse being somewhat less than the involved "measurement surfaces". As seen from the expressions, the "measurement surface thicknesses" are approximately proportional with the distance. At long distances the position information are therefore more appropriately expressed as angle uncertainties.

Some comments should be made regarding tracking since an emitter will be positioned by a tracker algorithm using a sequence of measurements rather than a static position estimator, as analyzed here. Further, accurate frequency measurements may be available, adding to the tracking performance by Doppler information. However, as for the purpose of analyzing the likely tracking accuracy, the CRLB-method can be used. One then has to adjust for the reduced measurement errors by averaging repeated measurements with independent errors. However, systematic errors will not be reduced this way. A reduction factor of 2-4 of the nominal measurement accuracies might be achieved depending on the portion of systematic errors and the measurement update rate. As the target-sensor geometry will not change significantly during a measurement averaging time period in a tracker, the CRLB-analysis should be a valid approach for tracking also.

Frequency measurements may supply Doppler information by calculating the FDOA (Frequency Difference Of Arrival) similarly to the TDOA. FDOA contains information about the velocity of the emitter, but does not add to the position accuracy in the presented static analysis. However, a tracker may use this information for a quicker initial establishment of the emitter velocity, and also for a better tracking of the velocity avoiding additional position errors in case of target manoeuvres. Numeric calculations depend on assumptions about the tracker and target manoeuvres, and are outside the scope of this paper. However, the velocity information from FDOA can be drawn from the CEP of TDOA measurements. This depends on the fact that FDOA is proportional to the time derivative of the TDOA, the scaling factor being the frequency of the emitter signal. The CEP can be interpreted as speed after a proper scaling. The scale factor is the uncertainty of the frequency measurements divided by the product of the uncertainty of the time measurements and the emitter frequency. In this case the scale is close to 1/7 (100 Hz / (70 ns x 10 GHz) ). This means an emitter velocity uncertainty of approximately 3 m/s in the central region of Figure 5 and 6. The geometry of FDOA is the same as TDOA meaning that four sensors are necessary to get a 3-D speed vector from FDOA measurements only.

Only the accuracy aspect of position information has been treated here. Sufficient receiver sensitivity and sensor-coverage of the terrain to get the needed detections are assumed, but this may pose a problem. An additional problem is to correctly associate the measurements when several emitters are present in the same area, see Figure 4. This problem is here termed "deghosting", and is briefly mentioned in the next section.

## 6. Integrating the ESM-Sensors - Data Fusion

As described in the previous section, the ESM-data has to be "fused" in order to obtain an emitter position. To obtain maximum tactical information, a further fusion with the radar data is necessary, as described in section 4. The readers should be aware of the evolving literature on Data Fusion; a search on the Internet might be worthwhile. The framework given by the US DoD Joint Directors of Laboratories (JDL) Data Fusion Group has been dominating in the last decade, and is now subject to adjustment (11).

Figure 4 illustrates a sorting problem in the case several emitters are producing bearings at two or more sensors. Wrong combinations of bearings make up "ghosts", which have to be sorted out. Hopefully, simple signal characteristics or elevation measurements can do the job. If three or more sensors observe the scene, the "ghosts" can also be sorted out by having less crossing bearings than the real ones, or by having improbable speed or speed changes. Some of these techniques are used in a Bayesian framework in (12). In case of simultaneous observations by two or more sensors, time sequence characteristics of signals can be used, or a measured TDOA can verify the position of the intersection. Lastly, if the system can do "fingerprinting", each individual emitter will be sorted out, and the problem is solved. Some of these methods imply tight sensor coordination and integration. The hyperboloid intersections will also need "deghosting".

The theoretical aspect of estimation and tracking from combined measurements of radars and ESM-sensors should be well known, but practical experience seem to be rare. The use of a MST-algorithm (Multi Sensor Tracker) may seem an obvious choice at a first glance. However, even if theoretically best, a MST requires lot of work and detailed sensor knowledge. The involved sensors and the integrating MST-software might have to be delivered as a single unit, possibly reducing flexibility and modularity. A simpler and more flexible way to integrate ESM and radars is "graphical integration", which can be viewed as a first integration level. The "integration" is then performed in the mind of the operator when seeing the two sets of information on top of each other (graphically transparent). Actual ESM-data to present together with radar tracks are bearings, TDOA-hyperbolas, or ultimately ESM-tracks, all with associated uncertainty and hopefully properly identified. The ESM-system should be controlled from an operation level such that high sensitivity antennas can be directed against the positions of radar-tracks for additional track- information, possibly identification.

The suggestions above call for an independent ESM-system being the main coordinator of the ESM-sensors and "preprocessing" their data before a further integration. This obeys the principle "integrate similar sources first", as stated among other interesting principles in (13). "Preprocessing" should also be done in each sensor to relieve communication bandwidth and the central computing load. This should include averaging of measurements before transmitting in order to reduce the random errors of the measurements and enable the estimation of their characteristics which is important for achieving a near optimal central track estimation.

A relatively low rate communication channel is preferable for operational flexibility, possibly a rate of 64 kbits/s or less. Time synchronization, in case of TDOA, then has to be achieved by accurate local clocks that are externally coordinated, possibly by GPS. ESM-sensors observing some of the emitters of Figure 1 may produce a lot more data than it is possible to transfer through a channel of the suggested capacity. However, the signals normally exhibit some sort of regular patterns. According to a principle in information theory, only the "new" or "surprising" elements in the data need to be transmitted. This calls for a "momentary signal library" characterizing the detected signals to reduce the bandwidth by sending references to the library elements rather than the data itself. Such a library should be seen in relation to the emitter library used to identify the detected emitters. Suggested integration principles and architecture are illustrated in Figure 7.

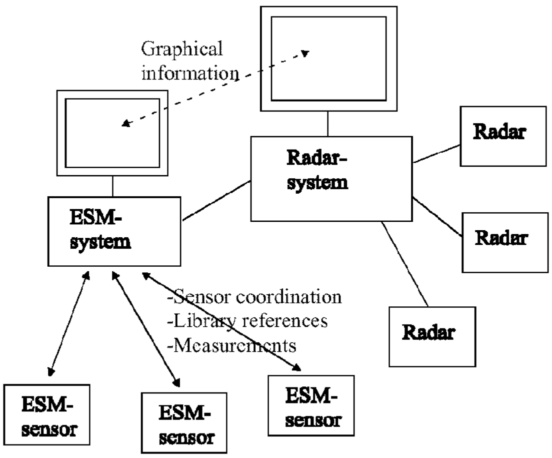


**Figure 7 Integration of ESM-sensors in a radar-based Air Defence System**

*The data from highly coordinated ESM-sensors are first "preprocessed" in an ESM-system which supplies identified bearings, TDOA-hyperbolas, and tracks as graphical overlays on the radar-system screen; graphical info is sent both ways. Cueing of the ESM-antennas from the radar system should be possible.*

## 7. Discussion of the Applicability of ESM-Sensors in Air Defence

There are several arguments for applying ESM-sensors in the air defence of an International Reaction Force, but there are also a number counter-arguments. The following is a discussion of some of the opposing arguments.

An International Reaction Force should pursuit information superiority in its undertakings. ESM-sensors are sources of information adding complementary data for building the general situation picture and good situation awareness. A counter-argument is that the significant sources of this information are the emitters controlled by the opposing adversary. Knowing the presence and possibly the capabilities of our ESM-sensors, he may choose to avoid using the emitters or using them in an unfavourable or misleading way for the Reaction Force. This counter-argument is hard to evaluate without knowing a lot more details. It can be argued, on a general basis, that the adversary by not using his emitters may restrict his abilities in a way that justifies the investment in ESM-sensors, even though they do not supply any information at all.

The stronger point of ESM-sensors compared to radars is identification. ESM-sensors should therefore be an obvious component of an integrated Air Defence System. Even more, electronic warfare jamming degrading the radars might be a valuable information source for the ESM. An important counter-argument is the effort necessary for collecting and updating an emitter-library vital for performing reliable and confident identifications. Such signal intelligence requires collection activity over a substantial time period. Further, collected emitter-data is sensitive information, and the use in an international setting might be difficult. Automatic identification might have to be supported by human decisions in critical situations. This requires manpower and proper education and training. The ESM-information might also be hard to integrate in a radar system, as indicated in section 6.

ESM-sensors are passive, small and relatively cheap compared with radars. Their number, ease of operation and silent presence make them hard to avoid, detect, or destroy by an adversary. They therefore significantly reduce his operational freedom. A counter-argument is that the ESM-sensors add to the cost of the Air Defence System, as they hardly can be used to reduce the number of radars. They will need a communication system, not likely that used by the radars. If some sort of radio communication is required, they might not be that difficult to detect after all. Further, even though the ESM-sensors are cheaper than radars, more sensors are needed to establish the same level of track information. Without very accurate direction measurement and dense sensor deployment, only TDOA-measurements might give a track accuracy near that of radars. Use of TDOA requires simultaneous detections by pairs of sensors, and three sensors have to be involved for obtaining an accurate position even with additional altitude information. Four are needed if the altitude of the object is to be deduced from the TDOA-measurement alone. Signal strength and terrain screening might then pose a problem for the required simultaneous detection in such a system. The accuracy "outside" the sensor area is poor compared to "inside"; this may pose a problem for a favourable deployment of the sensors.

## 8. Conclusion

The main purpose of this paper has been to present ESM-sensors as candidate sensors in a cost-effective integrated Air Defence System for an International Reaction Force, and to inspire investigations to clarify this question. As sketched, a number of threats normally emit signals that may be valuable sources of information about the situation. The characteristics of available ESM-sensors and those likely to be available on the marked in the near future exhibit a wide range of capabilities and prices. This is both an opportunity and a challenge for the design of a cost-effective system.

ESM-sensors may supply tactical information of different categories and should be seen in conjunction with a radar-based system. Emitter identification is the more important contribution, even if this requires substantial signal intelligence and emitter library handling. A tight coordination of the ESM-sensors improves their information. This includes the pointing and rotation of the ESM-antennas in order to increase simultaneous detections which are useful both for position accuracy and for "deghosting". We suggest to first integrate the data in an ESM-system before presenting information to a higher level in the Air Defence system by "graphical integration"; the latter being a first level of ESM/radar integration.

ESM-sensors should generally be regarded according to their name "support measures", but an ESM-system can theoretically by itself establish and maintain tracks with a position accuracy better than 100m. The position accuracy highly depends on the type of measurements made, their accuracy, and the sensor geometry. Fundamental principles and numerical results are presented to give a basic understanding and enabling a simple further analysis of this topic. If an adversary does not choose to fully use his airborne emitters, the tactical information support from the ESM-sensors is reduced, but so is the operational freedom of the adversary. The investment in ESM-sensors may also happen to be worthwhile in this case.

We believe that the technical development, both on the side of the defender and the adversary, points toward the use of ESM-sensors in an Air Defence System for an International Reaction Force. We hope this paper will inspire the interest in tactical ESM-sensors and that clarifications of these questions will be seen in the time to come.

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